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Statement of

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Saving Hubble Robotically: A Wise Choice

NAS Report Overstated Risks

Executive Summary

The mission to save the Hubble robotically began October 1, 2004, with a huge "running start." Key elements of the system, such as Dextre (the dexterous robot that will actually perform the servicing activities), are already built. Other major subsystems are "build to print" of existing technology or require little or no development.

Estimates of schedule – can the mission be launched before the Hubble degrades too far? – are key to evaluating whether the mission will be successful. The advisory reports (one from the Aerospace Corp. and one from the National Academy of Science) derived pessimistic schedule estimates from the faulty assumption that the program would begin from scratch, with a "blank sheet of paper". The real situation clearly contradicts this. One new piece of data is the delivery date for the robotic system: 31 months (Firm Fixed Price with penalties for late delivery.) This is less than half the 65 months assumed by the NAS. The actual facts about cost also challenge early estimates (e.g. robotic grapple arm is $25M versus Aerospace Corp. estimates of $700M).

Since the mission can be launched in time to arrive before the telescope is dead, the question that remains is technical risk. A key mission task entailing some risk is initially grappling or grabbing the telescope following rendezvous. This grapple task will be executed using a robotic grapple arm and "end effector" (or hand). The end effector will re-use an actual flight unit from the Space Shuttle manipulator, and the grapple arm for the mission is very similar to the existing Shuttle arms. Over 25 years, the Shuttle manipulator has executed 69 missions, including 142 grapple operations, without a single mission failure. This track record includes grappling the Hubble itself on 5 occasions.

In short, the NAS report significantly over-stated the risks associated with the robotic mission to save the Hubble.

The NAS report recommended a Shuttle-based rescue mission for servicing Hubble. If the decision were a simplistic man versus machine choice, the best choice would be astronauts. But if one asks the broader question: "How does NASA best deploy its Shuttles, astronauts, and robotic technology?", risking astronaut lives to change batteries seems shortsighted.

Finally, it was not within the scope of the NAS report to consider the value of the various mission options, beyond saving the Hubble. But the robotics mission has a clear advantage in this regard. For example, there is little of value to be learned by having astronauts do something they have done four times before. The capability for robotic servicing in space, on the other hand, is important to the future of science, national security and exploration.

To be more specific, since the future of astronomy is with large instruments outside the Shuttle's reach, robots that can service and upgrade them are likely crucial to the future of astronomy. For national security, the ability to robotically inspect and service large DOD assets in orbit is important. And the nation's exploration vision has already been explicitly articulated in terms of humans and robots working together. Robots will be necessary, for example, to assemble and maintain spacecraft, staging depots, and infrastructure.

To summarize, the robotic servicing mission will be successful saving the Hubble, while also contributing to the future of science, security and exploration.

1 Introduction

Good morning Mr. Chairman, Committee Members. It's a tremendous honor to be invited to be here, and it's a particular honor to be representing the team of extraordinarily motivated people working as we speak towards the Robotic Servicing Mission Critical Design Review in the fall.

I am Paul Cooper; I lead the space robotics business at MDA Space Missions, which for 25 years has been NASA's space robotics partner.

Let me first reinforce that saving the Hubble is an important and worthy goal; in fact, it is among our engineers' proudest achievements to have played a key role in the four earlier servicing missions, as well as the initial deployment of the telescope.

Among the options for servicing the telescope, we believe that the robotic servicing mission, already underway, is the right choice. In particular, we feel that the recently released reports from the National Academy of Sciences and the Aerospace Corporation have significantly overestimated the risks associated with saving Hubble robotically.

2 The Robotic Servicing Mission

I assume that the committee may already be aware of the mission profile for Hubble robotic servicing, but nevertheless here's a quick summary:

- Launch of Hubble Space Telescope (HST) Robotic Vehicle (HRV) on an Atlas V or Delta IV expendable launch vehicle.
- The HRV will consist of two separate spacecraft: the De-orbit Module (DM) and the Ejection Module (EM).
- HRV rendezvous with HST.
- Capture of HST using a 42 foot long Grapple Arm (similar to the Shuttle Robotic Arm but slightly shorter); the Grapple Arm will then be used to attach the HRV to the HST.
- Grapple Arm releases HST and picks up Dextre (or Special Purpose Dexterous Manipulator).
- Dextre is used to perform servicing mission tasks:
  - Robotically connect new battery packs to HST
  - Robotically connect new gyros to HST
  - Change-out Wide Field Camera
  - Change-out Cosmic Origins Spectrograph
  - Other servicing tasks
- At the conclusion of the HST Robotic Servicing Mission, the EM (along with all the robotic servicing equipment) will be separated from the HRV, leaving the DM attached to the HST.
- At the conclusion of (extended) HST scientific life, HRV-DM will safely de-orbit Hubble into the Pacific Ocean.

Figure 1 shows the Hubble with the HRV attached and the robots deployed.

The Hubble robotics servicing mission is also illustrated in a NASA movie that can be found at the NASA Goddard website (http://hubble.nasa.gov/missions/intro.php).

Figure 1: Hubble with the HRV Attached and the Robots Deployed

2.1 Mission Status

As of February 1, 2005 the mission has progressed significantly, and is on schedule for a late 2007 launch, beginning with an October 1, 2004 start date. The major subcontracts are in place (for the supply of the De-Orbit Module and the Robotic System), and a large team is ramped up and working at speed both within and outside of NASA.

The Mission Preliminary Design Review is scheduled for March 2005, with Critical Design Review to follow in early September 2005.

These “design” reviews suggest that the mission is still on the drawing boards. But due to the heavy re-use of existing technology, progress is far further ahead than one might envision.

For example, for the two major elements of the robot system, in one case (the use of the Space Station Dextre for Hubble instead of Station) the major components are already essentially complete, and where new hardware is being built (e.g. for the Grapple Arm), we have already begun cutting titanium forgings to make the new gears.

In another example, a few weeks ago NASA Goddard received a deliverable from Draper: software to control the spacecraft during autonomous rendezvous.

In other words, the robotic servicing mission is not a half-baked notional plan, but is a rapidly maturing reality being assembled from prior work.

3 Overall Orbital Robotics Track Record

Figure 2 is emblematic of the trust that NASA has developed in space robotics: not only does it show humans and robots working together, but it shows one of the space program's most valuable assets – an astronaut – literally hanging from a robot during Extra Vehicular Activity (EVA).

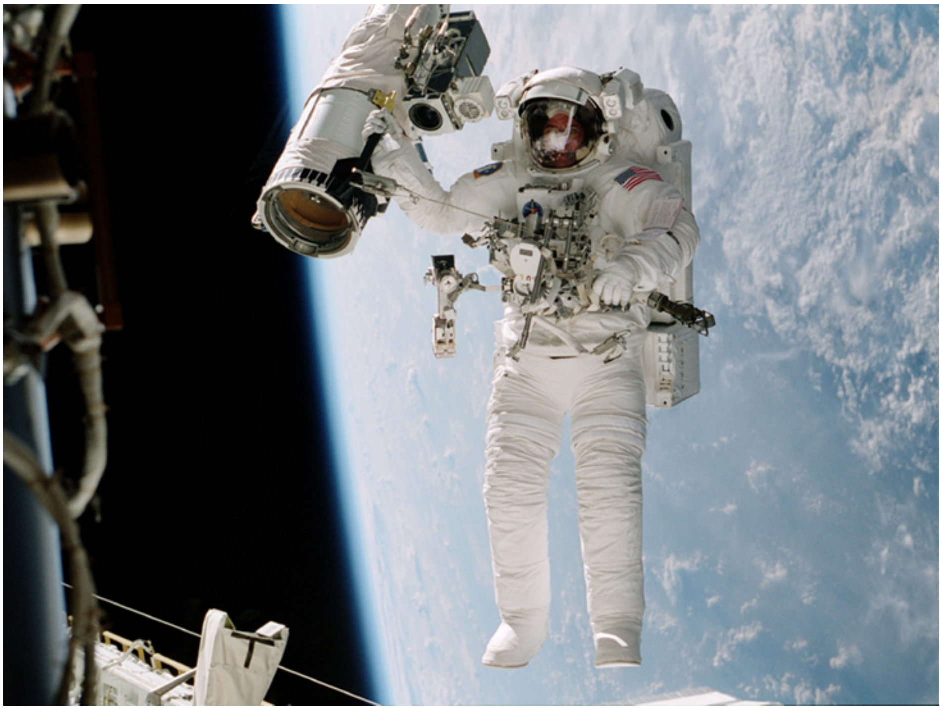

Figure 2: Shuttle Mission Photo Showing an Astronaut Attached to Shuttle's Robotic Arm

The most well-known space robot, the Shuttle Remote Manipulator System, has been flying since 1981. It has performed 69 missions without a single mission failure. The same system has also been successfully used four times to grapple the Hubble Space Telescope and to support subsequent EVA servicing missions for the Hubble.

This track record is particularly relevant because the robotic servicing mission plan calls for the use of a robotic arm nearly identical to the Shuttle arm, including the re-use of a actual Shuttle flight "end effector" (the "hand" on the end of the arm).

More recently, new robotic systems have been developed for the construction and maintenance of the International Space Station, including Dextre, to be described momentarily. Unmanned robotic missions for DOD applications in Low Earth Orbit (LEO) have also been developed.

Beyond LEO, the heritage and operational reliability of the many robots that have been the workhorse of planetary science are relevant, include the current MER rovers on Mars.

4 Aerospace Corporation Report

In our opinion, the Analysis of Alternatives report from the Aerospace Corporation was overly pessimistic in its view of robotic servicing. Table 1 summarizes our view of the difference between what are now known facts concerning the robotics elements, and what the report asserted.

Table 1: Elements of the Mission Compared

Element	Aerospace Corp. Study Assertion	Space Robotics Fact
Cost	$700M for grapple arm. >$2B for mission.	$154M Firm Fixed Price! For grapple arm *and* copy of Dextre.
Schedule	66 months	31 months with penalties
Development risk	High	Very low, since mission uses hardware that is already built
Mission risk	High	25 years, 69 missions, no mission failures

4.1 Cost

The Aerospace Corporation report has suggested that a Hubble Robotic Servicing Program will cost more than US$2B, with a grapple arm incremental cost of approximately US$700M. The fact of the matter is that MDA has entered into a Firm Fixed Price Contract with NASA at US$154M to provide a grapple arm plus a dexterous robot and other accessories. (The share of the contract devoted to the grapple arm amounts to $25M.)

4.2 Schedule

The Aerospace Corporation report suggested that a Hubble Robotic Servicing Program will take at least 66 months to execute. Again, the fact is that on the robotics portion of the mission, MDA has contractually committed to NASA to deliver the robotics systems within 31 months, with the potential for negative financial consequences if delivery is late.

As for the spacecraft portion of the mission, the Aerospace Corporation has drawn their schedule conclusion based on a diverse and not necessarily compatible data set, including a mix of manned and unmanned missions, U.S. and foreign Programs, and so on. As shown in Figure 3, a very different perspective will emerge using data points that reflect new spacecraft development that is not “done from scratch” but nonetheless yields a new integrated product. We believe that this perspective is representative of the current Hubble Robotic Servicing Program run by NASA Goddard, which maximizes the use of existing technologies and subsystems to support a “running start” and not a “white sheet of paper” approach. This approach suggests that a roughly 40 month schedule for the Program is entirely plausible, and not the 66 month schedule that has been suggested.

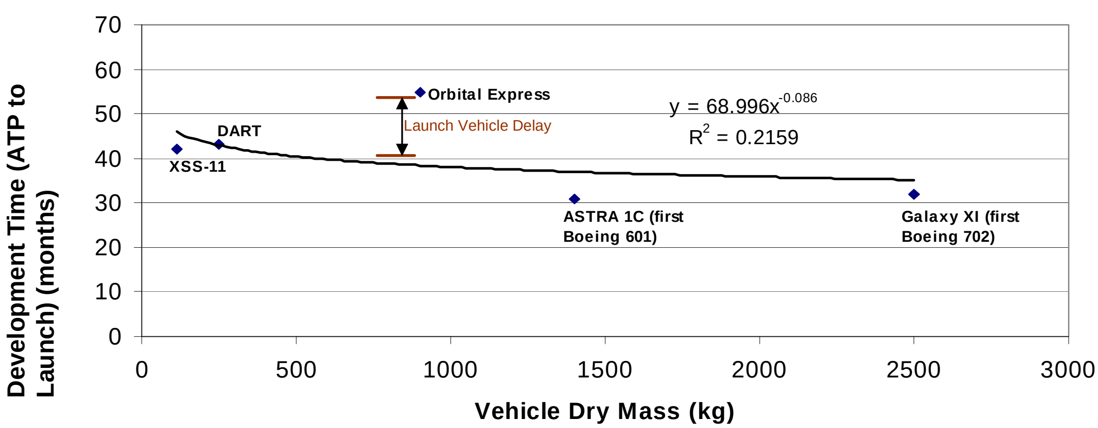

Figure 3: Schedule Estimate Results Analogous to Aerospace Corp. Report

4.3 Development Risk

4.3.1 Robot System

The Aerospace Corporation report suggested that a Hubble Robotic Servicing Program has high development and mission risks. Development risk is defined as the risks associated with preparing the mission in time. Mission risk is defined as the risk associated with executing the mission successfully. (Although for the NAS mission risk was defined as the risk of failing to achieve mission objectives).

The overall evaluation was dominated by the estimate of the schedule necessary to mount the mission. In short, if the telescope has a high likelihood of being dead by the time the rescue mission reaches it, the mission is a failure.

Because the Robot System for Hubble servicing either uses hardware that is already built or leans heavily on existing hardware, there is practically no development risk. The primary example is Dextre. A picture of the completed and flight-qualified Dextre, hanging in our Cleanroom, is shown in Figure 4. This is the *actual robot that will be used to service the Hubble*; the only planned change is to add an additional camera. (A copy of Dextre will be built for later use on the Space Station).

Figure 4: Dextre Flight Hardware

For another extremely important element of the Robot System -- the End Effector that will actually grapple the Hubble and pick up Dextre – the plan is to re-use a Shuttle flight unit that has already successfully performed this critical operation on orbit dozens of times.

In short, for the Robotic System, development risk is minimal. Hence the willingness of the contractor to enter into a Firm Fixed Price contract with a 31 month schedule.

4.3.2 Other Mission Elements

Is there then some other critical mission element that *is* being developed from scratch, for which the assumed schedule of 66 months makes more sense? The answer, in short, is no. The de-orbit vehicle is also on an approximately 30 month schedule, and maximizes re-use of existing technology. A key sensor for the rendezvous (the “lidar”) is a re-build of a sensor just delivered a few months ago for a separate mission. The situation is similar for basically all the key components of the mission, including the software for controlling the spacecraft during rendezvous.

4.4 Mission Risk

The Aerospace report analyzed “mission risk” as the concatenated probability of failure of specific subsystems and mission tasks.

As a starting point, consider the Aerospace analysis of the probability of mission success for the De-Orbit Option using a grapple arm: 93%. A key thing to understand about the De-Orbit mission profile is that *it contains almost all the significant risks of the servicing mission*, specifically the need to autonomously rendezvous with and grapple a potentially tumbling telescope.

Once the telescope is grappled and the rescue vehicle is berthed, the mission risk reduces down to the risk of successfully executing the specific repair and upgrade operations.

But while the Aerospace report was guessing at the likelihood of specific component and task failures, NASA Goddard (working in concert with engineers from MDA Space Missions) *was systematically performing each operation using real hardware* – that is, using the earth-bound version of Dextre operating on the Hubble high fidelity mockup.

NASA summarized this intensive risk retirement activity in this way: “A space-flight qualified robot has successfully demonstrated that all life-extension tasks and science instrument change-outs can be robotically performed”. (A comprehensive list of the tasks performed and the dates upon which they were executed is included in Appendix C).

It would be difficult to do further work to retire mission risks; the next logical step is to actually execute the mission. Based on these new facts, one can now estimate the likelihood of successfully executing the whole servicing operation as similar to the likelihood of succeeding at the de-orbit mission, e.g. in the 90 percentile range.

4.5 Summary on Aerospace Report

I would like to summarize our reaction to the Aerospace Corporation Report as follows:

- Aerospace Corp. Reported Baseline Assessment for Robotic Servicing Program:
  US$2B, 5.4 years, high development risk, high mission risk
- Alternative Assessment:
  ~ US$1.3B, 3.5 years plausible, little development risk, 90% or higher probability of mission success

5 National Academy of Sciences (NAS) Report: Risk Overstated

5.1 Overall Mission Risk Appraisal

The NAS report concluded with a remarkably pessimistic appraisal about the prospects for the robotic mission: an 80% chance of mission failure is asserted.

This seems to fly in the face of everything known about the track record of space robotics, so how could this conclusion have been arrived at? The assertion is derived mainly from two guesses: a guess as to how long it will take to mount the mission, and a guess as to how slowly the Hubble will degrade, i.e. in what state will the telescope be when the robotic rescue mission reaches it?

The NAS report inherited its schedule assumptions in large part from the Aerospace report, and the same consequences follow as described earlier. Since in reality the Hubble robotic rescue is starting from a "running start" (e.g. maximal utilization of existing technology) we can reasonably expect the mission to be launched before the telescope degrades to the point where it cannot be repaired.

Also, continuing progress is being made in slowing the Hubble's rate of degradation, further mitigating the risk to mission success from schedule. If the risks due to schedule are removed, what remains as a real threat to the mission's success are technical risks.

5.2 NAS Technical Risks

The NAS report identified a number of areas of technical concern. We discuss these risks, and highlight in particular the risk mitigation progress that has been made since the report was published.

5.2.1 Grapple Events

The NAS report expressed concern that each grapple event was a source of risk, e.g. initially grappling the telescope, releasing the telescope, and subsequently grappling Dextre[1]. Each event requires making a mechanical connection and in the case of grappling Dextre, establishing an electrical connection as well.

In a nutshell, this concern is misplaced. The mission plan calls for the re-use of a reliable End Effector from the Shuttle robotic arm, proven through dozens of uses in space. Literally hundreds of grapple operations have been performed with identical hardware over the past decades. (Appendix A summarizes the performance of the Shuttle Remote Manipulator System).

5.2.2 Time-delayed Control

The NAS report expressed concern about the risks related to operating on-orbit robots from the ground via time-delayed control[2]. There is no doubt that time-delay will be present when controlling the robots, since for example, the signal will travel via the TDRSS data relay satellite.

Since the report was issued, two significant developments have transpired that suggest the risks inherent in time-delayed control are less than the NAS report suggests.

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[1] National Research Council of the National Academies (2004) Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report. Page 63-66.
[2] National Research Council of the National Academies (2004) Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report. Page 63.

First, following a 1-year review process, ground control of Space Station robotics recently passed the NASA Space Station Safety Review panel in September 2004. This process was driven by need: astronaut time on-orbit is scarce and valuable, and if robots can perform mundane tasks while controlled from the ground, on-orbit productivity will increase. (This same trade-off applies more broadly for the Hubble mission). As one can imagine, the safety review involved an extreme in-depth scrutiny of the risks involved with time-delayed control of on-orbit robots. Ground control is set to be commissioned on-orbit in February 2005. There is no doubt that during 2005 (prior to the Hubble robotic mission CDR in the fall), much will be learned from operational experience. These lessons can be incorporated into planning for the Hubble mission, which uses substantially the same ground control system.

Second, risk mitigation testing specifically aimed at addressing this question has been ongoing at Goddard. Since the NAS report, numerous tests of the earth-bound version of the Dextre robot have been performed. Shuttle astronauts at the Johnson Space Center remotely operated the robot at NASA Goddard to extract the Wide Field of View Camera 2 (WFOC-2) and insert the WFOC-3 overcoming technical challenges such as control time delays of 2 seconds. In a separate set of tests, variable control time delays of up to 8 seconds were generated during the extraction of the COSTAR instrument and replacement of the COS instrument. These tests independently varied the video and force feedback time delays. Other tests have demonstrated that astronaut control is achievable even in operations in which astronauts are provided with inadequate camera views of the worksites. Our testing shows that the mission is wholly feasible under the constraints of time delay.

5.2.3 Autonomous Rendezvous

The NAS report highlights the risk of autonomous rendezvous as one of the most serious to be faced by the mission. In fact, the report asserts that this "has never been done" [3].

Russian spacecraft have been routinely executing automatic rendezvous and docking missions using technology developed in the early 80's. Table 2 summarizes autonomous rendezvous and docking with Russian spacecraft.

Table 2: Russian Spacecraft Autonomous Docking Since 1987

Spacecraft	Number of fully automatic dock/undock operations	Timespan
Spacecraft to MIR Space Station	101	1987-2000
Spacecraft to International Space Station	28	2000-2005
Total	**129**	

The importance of autonomous rendezvous and proximity operations has been recognized by the U.S. space community for some time. As a result, there has been a significant development activity in place for many years, and a sequence of missions is planned to validate and demonstrate these capabilities. All these missions will fly prior to the Hubble mission, with time enough to incorporate "lessons learned". Missions devoted to examining autonomous rendezvous and/or capture/docking include include the XSS-11 mission for the Air Force Research Labs (scheduled for launch March 2005), the DARPA Orbital Express mission (scheduled for launch in 2006), and the DART mission.

The initial concepts for rendezvous and capture were developed during the Gemini and Apollo programs. The Shuttle has demonstrated that these can be performed for a more general set of LEO missions and has developed a wide variety of approach trajectories and control strategies. These missions demonstrated many of the automated guidance, navigation and control functions required today for autonomous rendezvous and capture. For both Apollo and Shuttle, the rendezvous planning was performed on the ground, but the onboard system was able to target and automatically control the rendezvous burns. The final capture/docking phase was controlled manually by the crew. The Shuttle onboard GN&C is able to automatically perform many of the necessary rendezvous functions, including relative navigation, targeting and control. Attitude control is done automatically, and translational control is done manually based upon Rendezvous and Prox Ops Planner (RPOP) software that runs on a laptop computer in the cockpit.

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[3] National Research Council of the National Academies (2004) Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report. Page 63.

The crew enters data into the laptop from the hand-held radar and the Trajectory Control Sensor (LIDAR), and the RPOP program computes the burn plan. The crew manually performs the final docking maneuvers using the cameras and data from the vision sensors. The Hubble Robotic Servicing mission will require full automation of these functions, but the fundamental techniques for rendezvous, proximity operations, and capture of a stable target have been adequately demonstrated.

The significant remaining technical issues that need to be addressed for the AR&C phase of the Hubble Robotic Servicing mission are the autonomous operations, and the relative sensing and subsequent capture of a tumbling target.

XSS-11

As of Feb 1, 2005, the XSS-11 spacecraft is being fueled for launch in a few weeks. The automation aspects of autonomous rendezvous are fully addressed with the XSS-11 mission plan, which will perform completely several fully autonomous rendezvous and operations in proximity to several uncooperative targets. The software to affect an autonomous rendezvous and capture has been developed and tested in a 6 degree-of-freedom(6DOF) gantry facility at Lockheed Martin.

A version of this software suitable for the Hubble mission rendezvous and proximity operations from long range into a 10 foot offset point has been developed by Draper Lab, and has already been delivered to Lockheed for the purpose of conducting simulation demonstrations of the autonomous Hubble rendezvous and capture.

The XSS-11 mission relies on a laser-based Lidar vision system for rendezvous and docking. By detecting the reflection of a laser beam, the Lidar will detect features on objects that are less than half an inch in size from a distance of almost two miles. The same Lidar will be used on the Hubble Robotic servicing mission.

The on-orbit performance of the entire XSS-11 rendezvous system, including sensor, will be known by the September 2005, when the Critical Design Review is scheduled for the Hubble robotic mission.

In addition, extensive ground validation of the autonomous capture operations is ongoing for the Hubble Robotic Servicing mission. The 6DOF proximity operations necessary to match the rotation of a tumbling HST have been demonstrated in a high fidelity simulation by Draper Lab. It should be noted that the estimated worst case rotation rate is very slow at 0.22 deg/second (or only 2.2 revolutions per hour).

5.2.4 System Integration

The NAS report also highlighted the risks associated with the overall task of integrating and testing the entire system. Since the NAS fact finding sessions, the program has actually begun, and NASA Goddard has substantially matured its plan for System Integration. This plan is included as Appendix B.

5.2.5 Robotic Repair Operations Actually Performed on Hubble Mockup

One thing that was remarkable in its absence from the NAS report was any discussion of the extensive efforts that have gone on at Goddard in the past year to *prove*, by having the ground test-bed version of Dextre actually execute the operations on the high fidelity mockup of Hubble, that all the operations could be executed. In other words, predominately *since* the NAS report fact finding, a space-flight qualified robot has successfully demonstrated that all life-extension tasks and science instrument change-outs can be robotically performed.

Appendix C describes these operational tests in more detail.

5.3 Robotics' Risk Summary

5.3.1 The Robotic Mission Will Have Time and be Flexible

Perceptions of how the robots will operate can affect inferences about associated risk. Sometimes, it seems like people imagine that the robotic rescue mission is going to be like a car assembly operation -- that it can only be done one way and if that way fails we're stuck. Alternatively, people imagine that while an astronaut is driving the robot from on the earth, something is going to happen really fast that we won't be able to deal with.

But both these perceptions are wrong.

Previous Shuttle-based Hubble Servicing Missions, although very successful, have relied on quick execution of EVA tasks on a very tight timeline that is counted in hours and days.

The robots, however, won't need oxygen, and we'll have lots of time – weeks or months if necessary -- to go slow, evaluate what's happening, make adjustments, make multiple attempts at operations, and re-plan if necessary. For example, we have two arms to use, even though the nominal operations plan calls for using only one most of the time.

We have seen with the current Mars rovers a very compelling example of how robots can recover from problems, and do amazing things in *much* more difficult circumstances (e.g. much longer time delays for control) than what we are looking at for Hubble.

In short, the robot mission will be much more flexible than people imagine.

5.3.2 The Next Step: Fly the Mission

It is our opinion that the robotic risks for the Hubble robotic servicing mission have been largely overstated by the NAS report. Key identified risks in autonomous rendezvous and grapple have either already been largely demonstrated or are to be fully demonstrated on missions such as XSS-11, DART and Orbital Express. Ground control of Space Station robot has already passed NASA safety review and is scheduled for a first demonstration in February 2005. Critical Hubble servicing robotic operations have been tried-out on the ground using flight-representative robotic and Hubble mockups remotely operated over long distances. The key robotics risks for the mission, in our opinion, have hence been largely retired, and the next logical step is actually to fly it.

6 Alternative Mission Options

6.1 Shuttle Servicing Option

The NAS report recommends using a Shuttle mission to service the Hubble. If one allows for the possibility that a robotic mission is likely to be successful, a robotic option becomes the preferred option.

On this question there is no debate: “Which is more intelligent and flexible, astronaut or robot, and thus more likely to succeed in performing Hubble servicing activities?” Everyone would agree that an astronaut is more likely to be successful. This is not, however, the fundamental question needing to be addressed.

The broader question is something more like: “Given the available assets for use in space, including Shuttles, astronauts, robots, ELVs, etc. what is the best way of allocating these assets to the tasks to be accomplished?”

Servicing the Hubble robotically has compelling value when considered in this light:

1) It liberates scarce resources – Shuttles and astronauts – for other tasks that *cannot* be achieved using a robotic mission
2) It allows the Shuttle to be retired sooner
3) Astronaut lives are not risked on this mission
4) A capability is developed that can be used on other missions (this is described momentarily)

Astronauts changing batteries? It appears short-sighted, and certainly we will need other more economically appropriate alternatives in the long run.

6.2 De-orbit Only Option

It is our understanding that at a minimum, a robotic de-orbit mission of the Hubble has to be mounted, in order to avoid an eventual uncontrolled re-entry of the telescope, and thus ensure public safety. The Aerospace Corporation report asserted that a de-orbit mission using a robotic grapple arm for Hubble capture has a 93% probability of mission success.

From a robotics point of view, the key fact about a de-orbit mission is this: *adding servicing to a de-orbit mission adds only relatively small incremental risk and cost*. Put another way: Since the key mission risks of “autonomous rendezvous and grapple” are the same for the servicing and de-orbit missions, why not do the servicing too?

This logic is particularly compelling if the telescope is dying anyway, and there is little to lose by trying to fix it. The servicing mission will only add incremental costs and small incremental risks, while producing very significant paybacks.

6.3 Re-hosting

Another alternative that has been proposed is re-hosting the science instruments intended for the Hubble upgrade on another new platform similar to the Hubble.

It is certainly beyond the scope of this witness to comment on the technical and economic challenges of building space telescopes, and the potential science value that may result.

It may perhaps be useful to note, however:

A new telescope contributes nothing to the Hubble problems – at a minimum, a still-expensive de-orbit-only mission must be mounted for Hubble. But the incremental cost of adding servicing to a de-orbit mission is certainly much less than the cost of developing a re-hosting solution.

Unlike the robotic mission, constructing a new telescope is unlikely to make a substantial contribution to any other space mission goals.

7 The Future

Unlike the other options for servicing the Hubble, developing a robotic servicing capability would be extremely valuable for other national needs in space.

7.1 Science

The future in astronomy is to place larger instruments well beyond low Earth orbit, for example at Lagrangian Points such as L2 (which is beyond the moon). These distances are so far that they are beyond the reach of the Shuttle. Robotic servicing offers scientists the ability to upgrade these instruments as our knowledge of the universe unfolds. The Hubble Robotics Servicing Mission will provide scientists with a proven method for building ever better instruments.

7.2 National Security

Akin to extending the life of the Hubble Space Telescope, the Department of Defense (DOD) is seeking to extend the life of critical military space assets by performing on-orbit servicing. The XSS-11 and Orbital Express missions are developing and testing the necessary technologies for servicing military satellites on-orbit. The DOD has decided to use robots for autonomous rendezvous and docking, refueling, repair and other tasks. The DOD will benefit from the experiences gained on the Hubble Robotics Servicing Mission.

7.3 Exploration

Future Space Exploration Programs will undoubtedly need to maximize sustainable affordability, maximize safety, improve mission success effectiveness and advance the state-of-the-art with each mission. Future missions will also need to achieve the right balance between humans and robots working collaboratively, given some of the far mission locations and the high costs and complexity of conducting human-only missions. Robotics advancement will open new alternatives that can contribute increased safety and mission success, while lowering overall mission costs. NASA is already embarking on its vision to use humans and robots in tandem to explore the universe. Humans are to perform the analysis and discovery and manage dynamic environments while robots will complement humans by performing routine tasks such as the maintenance of spacecraft staging depots and infrastructure.

More specifically, the proposed Hubble Robotics Mission will serve as a key stepping stone for NASA's new vision for Space Exploration, by acting as a precursor and testbed for effective closely coupled human and robotic partnerships in Exploration. Astronauts have already well proven themselves on previous Hubble Servicing and other manned missions in Low Earth Orbit and on the moon. Now is the right time to extend the reach of astronauts by introducing more sophisticated remotely operated robotic capabilities.

Appendix A: End Effector Operational Track Record

Description of Operation	Total Number of Operations
Total SRMS End Effector Flights	69
Total SRMS on-orbit End Effector Actuations	436 (includes end effector checkouts)
Total SRMS payload grapples	142 (inlcudes both fixed and free-flyer grapples)
Total SRMS Free-Flyer grapples	33 (inlcuding HST 4 times)

SRMS end effector failures = none. All the above were 100% successful.

Appendix B: System Integration Plan for the Hubble Robotic Servicing and De-orbit Mission (HRSDM)

HRSDM is truly a large system to design, develop, integrate, test and verify, within a 39-month start to launch period of performance. This was accommodated during selection of architecture through an approach that focuses on a modular, relatively independent, implementation. This includes:

- Stand alone De-orbit Module based on a proven spacecraft.
- Existing Robot System with International Space Station heritage.
- New GSFC developed Ejection Module with high commonality with De-orbit Module spacecraft bus architecture.
- An evolving Ground Station made up of existing HST ground equipment augmented with equipment used during HRSDM elements integration and test program.
- Existing HST science replacement hardware ready for incorporation into the Hubble Space Telescope.

The implementation approach described above has three major features that will facilitate System I&T. First, each of the major program elements will be independently integrated, tested and verified against their respective requirements. During that integration and test process, simulators from the interfacing elements will be used for interface validation.

Second, a full up System Integration and Test Program of all of the elements at GSFC starting January 2007 one year prior to launch, will validate all system interfaces and complete Element Level environmental test.

Third, all of the Element Level ground station hardware and software that will be used to test the various elements at their developer's facilities, will be delivered to GSFC for final HRSDM Level Integration and Test and will remain at the Mission Operations Control Center through the Servicing Mission, as applicable, through the eventual De-orbit Mission.

The GSFC existing facilities, the just-in-time deliveries of the HRSDM elements, and the preliminary System Level integration during Element I&T are major contributing factors of a rigorous, albeit short, implementation program. However, the principal contribution is the use of existing personnel experienced on four prior servicing missions who have demonstrated their ability to meet launch dates without compromising mission integrity. Building of EM in-house allows the personnel to get involved early throughout the EM I&T program. As Robotic System hardware, EM spacecraft, and HST payloads become available, they will be interfaced and tested along with their appropriate ground stations. This enables a team to start into System Level I&T during EM testing from September 2006 through January 2007. During the February 2007 through May 2007 as the other elements are delivered, this experienced team will integrate the elements into the Mission System.

This still leaves six full months for System Level testing, mission simulations and requirements verifications, before delivery of the mission to KSC for launch.

Throughout the mission the same trained and experienced work force will man the Ground Stations, operate the HRSDM Elements, service the HST and de-orbit the Ejection Module spacecraft.

Appendix C: Hubble Mockup Testing

Since March 2004, engineers have been testing an earth bound version of Dextre to determine if all of the Hubble servicing tasks can be accomplished robotically under the actual operation scenario which includes various degrees of camera views, transmission time delays and variable lighting conditions. These tests are summarized below.

AT MDA

15/3/04 – 07/04/04

SSM BAY 1 – (486 COMPUTER)
J LATCH LOCKING FEATURE UNDONE
J LATCHES ROTATED
DOOR OPENED
P9 TERMINATOR PLUG REMOVAL FROM J9
INSTALLATION OF 1553 DATA BUS CONNECTOR ONTO J9
DOOR CLOSED

DIODE BOX
REMOVAL OF P6A PLUG FROM DIODE BOX
INSTALLATION OF P6A PLUG ONTO TEMP STOW BRACKET
REMOVAL OF P8A PLUG FROM DIODE BOX
INSTALLATION OF P8A PLUG ONTO TEMP STOW BRACKET

AT GODDARD SPACE FLIGHT CENTRE

30/04/04 – 10/05/04

WIDE-FIELD CAMERA
INSTALLATION OF GROUND STRAP TEMP STOW BRACKET
GROUND STRAP REMOVAL FROM WIDE-FIELD CAMERA 2
GROUND STRAP INSTALLATION ON .TEMP STOW BRACKET
WIDEFIELD CAMERA 2 REMOVAL
WIDEFIELD CAMERA 3 INSERTION
GROUND STRAP REMOVAL FROM TEMP STOW
GROUND STRAP INSTALLATION ON WIDE- FIELD CAMERA 3

12/05/04 – 18/05/04

REMOTE DEMONSTRATION OF WIDEFIELD TASKS FROM JSC
CREW TRAINING @ GODDARD FOR WIDE-FIELD TASKS
CREW TRAINING @ JSC FOR WIDE-FIELD TASKS
CREW REMOTE DEMONSTRATION FROM JSC
(GROUND STRAP AND WIDEFIELD REMOVAL INSERTION TASKS, WITH LATENCY – 2 SECONDS ON VIDEO, TELEMETRY INSTSANTANEOUS)

19/05/04 – 28/05/04

COSTAR/COS TASKS

INSTALLATION OF “COME-ALONG” TOOL TO RESTRAIN DOOR
UN-TORQUE AND ROTATE LATCHES
OPEN DOORS
REMOVE CONNECTORS FROM COSTAR (J1, J2, J3, J4.)
INSTALL CONNECTORS ON CONNECTOR TEMP STOW PANEL (J1, J2, J3, J4.)
REMOVE GROUND STRAP FROM COSTAR
INSTALL GROUND STRAP ON C.T.P
CLOSE DOORS USING “COME-ALONG” TOOL
ROTATE AND TORQUE DOOR LATCHES
REMOVE “COME-ALONG” TOOL

18/06/04 – 23/07/04

COSTAR/COS TASKS – CONTINUED

INSTALLATION OF “COME-ALONG” TOOL TO RESTRAIN DOOR
UN-TORQUE AND ROTATE LATCHES
OPEN DOORS
INSTALL DOOR RESTRAINT
INSTALL CONNECTOR TEMP STOW PANEL
REMOVE CONNECTORS FROM COSTAR (J1, J2, J3, J4.)
INSTALL CONNECTORS ON CONNECTOR TEMP STOW PANEL (J1, J2, J3, J4.)
REMOVE GROUND STRAP FROM COSTAR
INSTALL GROUND STRAP ON C.T.P
MOVE C.T.P TO HANDRAIL
INSTALL B LATCH TOOL
REMOVE COSTAR
INSTALL COS
REMOVE B LATCH TOOL
INSTALL C.T.P TO COS
REMOVE DOOR RESTRAINT
CLOSE DOORS USING “COME-ALONG” TOOL
ROTATE AND TORQUE DOOR LATCHES
REMOVE “COME-ALONG” TOOL

08/09/04 – 08/10/04

+V2 CONDUIT

ATTACH CONDUIT TO NC RADIATOR
RETRIEVE R& P CONNECTION TO DM
RETRIVE SA UMBILICAL BRACKET
RETRIEVE AND MATE CONNECTION TO NCS RADIATOR

WIDE-FIELD CAMERA

INSTALL ADAPTOR PLATE TO WIDE-FIELD CAMERA
ACCESS A LATCH
ACQUIRE BLIND MATE CONNECTOR MECHANISM

LATENCY TESTS

CONTROLLED TESTS OF LATENCY EFFECTS
VIDEO AND TELEMETRY LATENCY ADJUSTED INDEPENDENTLY
VIDEO AND TELEMETRY LATENCY TESTED FROM 2 SECONDS TO 8 SECONDS
TASKS PERFORMED WITH LATENCY INCLUDE:
COSTAR REMOVAL /COS INSERTION
-V2 DOOR LATCH BOLT ACTIVATION

VISION SYSTEM

CONTROLLED TESTS OF VISION SYSTEM
VISION USED TO ASSESS POSITION BY MODEL MATCHING
-V2 DOOR LATCH SUCCESSFULLY ACQUIRED, UNTORQUED, AND ROTATED, WITHOUT ASSISTANCE OF VIDEO.

29/11/04 – 17/12/04

-V2 AFT SHROUD DOORS

INSTALLATION OF “COME-ALONG” TOOL TO RESTRAIN DOOR
UN-TORQUE AND ROTATE LATCHES
OPEN DOORS
CLOSE DOORS USING “COME-ALONG” TOOL
ENGAGE SHEAR PLATES
ROTATE AND TORQUE DOOR LATCHES
REMOVE “COME-ALONG” TOOL

SSM BAY

UNTORQUE AND ROTATE J LATCHES

FINE GUIDANCE SYSTEM

REMOVE CONNECTORS
INSTALL CONNECTORS ON C.T.P

DIODE BOX

REMOVE CONNECTORS
INSTALL CONNECTORS ON C.T.P

COSTAR/COS

REMOVE AND INSTALL CONNECTORS

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